

Gamma-ray background from structure formation in the intergalactic medium

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The universe is filled with a diffuse and isotropic extragalactic background of γ -ray radiation¹, containing roughly equal energy flux per decade in photon energy between 3 MeV–100 GeV. The origin of this background is one of the unsolved puzzles in cosmology. Less than a quarter of the γ -ray flux can be attributed to unresolved discrete sources^{2,3}, but the remainder appears to constitute a truly diffuse background whose origin has hitherto been mysterious. Here we show that the shock waves induced by gravity during the formation of large-scale structure in the intergalactic medium, produce a population of highly-relativistic electrons with a maximum Lorentz factor $\gtrsim 10^7$. These electrons scatter a small fraction of the microwave background photons in the present-day universe up to γ -ray energies, thereby providing the γ -ray background. The predicted diffuse flux agrees with the observed background over more than four decades in photon energy, and implies a mean cosmological density of baryons which is consistent with Big-Bang nucleosynthesis.

The universe started from a smooth initial state, with small density fluctuations that grew in time due to the effect of gravity. The formation of structure resulted in non-relativistic, collisionless, shock waves in the baryonic gas due to converging bulk flows, and raised its mean temperature to $\sim 10^7$ K ($= 1$ keV) at the present time⁴. This is indeed the characteristic temperature of the warm gas in groups of galaxies, which are the typical objects forming at the present epoch. The intergalactic shocks are usually strong, since the gravitationally-induced bulk flows are often characterized by a high Mach number. The intergalactic gas may have also been heated by shocks driven by outflows from young galaxies^{5–7}.

Collisionless, non-relativistic, shocks are known to generically accelerate a power-law distribution of relativistic electrons, with a number density per electron momentum, p_e , of $dn_e/dp_e = Kp_e^{-\alpha}$, where K is a constant⁸. The power-law index for strong shocks in a gas with an adiabatic index $\Gamma = 5/3$, is^{8–10}, $\alpha = [(r+2)/(r-1)] = 2$, where $r = [(\Gamma+1)/(\Gamma-1)]$ is the shock compression factor. Such an electron distribution is found in the strong shocks surrounding supernova remnants in the interstellar medium⁸. Recent X-ray^{11,12} and TeV^{13,14} observations of the supernova remnants SN1006 and SNR RX J1713.7–3946 imply that electrons are accelerated

in the remnant shocks up to an energy ~ 100 TeV, and are confined to the collisionless fluid by magnetic fields. These shocks have a velocity of order 10^3 km s $^{-1}$, similar to the velocity of the intergalactic shocks we consider here. The inferred energy density in relativistic electrons constitutes 1–10% of the post-shock energy density in these remnants, a fraction consistent with the global ratio between the mean energy density of cosmic-ray electrons and the turbulent energy density in the interstellar medium of our galaxy.

Since the physics of shock acceleration can be scaled up to intergalactic distances, it appears natural to assume that a similar population of relativistic electrons was also produced in the intergalactic medium. The maximum Lorentz factor of the accelerated electrons, γ_{\max} , is set by equating their acceleration and cooling times. The e -folding time for the acceleration of the relativistic electrons is $t_{\text{acc}} \sim (r_L c / v_{\text{sh}}^2)$, where $v_{\text{sh}} = (\Gamma + 1)[kT / (\Gamma - 1)m_p]^{1/2}$ is the shock velocity relative to the unshocked gas, m_p is the proton mass, and r_L is the electron Larmor gyration radius. For an electron with a Lorentz factor γ_e , $r_L = 5.5 \times 10^{-2}(\gamma_e / B_{-7})$ pc, where $\gamma_e = (\gamma_e / 10^7)$, and B_{-7} is the magnetic field strength in units of $0.1 \mu\text{G}$. A magnetic field amplitude of $0.1\text{--}1 \mu\text{G}$ is often detected in the halos of galaxy clusters^{15–17}. In particular, a magnetic field amplitude of $\gtrsim 0.1 \mu\text{G}$ was inferred on the multi-Mpc scale of the Coma–A1367 supercluster¹⁸, which provides a good example for the intergalactic structures of interest here. For such magnetic field amplitude we get, $t_{\text{acc}} \sim 2 \times 10^4$ yr $(\gamma_e / B_{-7})(kT / \text{keV})^{-1}$.

The acceleration time is much shorter than the lifetime of the intergalactic shocks, which is comparable to the age of the universe. The maximum Lorentz factor of the electrons, γ_{\max} , is therefore not limited by the lifetime of their accelerator, but rather by their cooling, primarily due to Compton scattering off the cosmic microwave background¹⁹. Synchrotron cooling is negligible for $B_{-7} \lesssim 10$. The characteristic cooling time due to inverse-Compton scattering is $t_{\text{cool}} = [m_e c / (4/3)\sigma_T \gamma_e u_{\text{cmb}}] = 1.2 \times 10^{10}$ yr $(\gamma_e / 200)^{-1}$, where m_e is the electron mass, σ_T is the Thomson cross-section, and u_{cmb} is the energy density of the cosmic microwave background. By equating the acceleration and cooling times, $t_{\text{acc}} = t_{\text{cool}}$, we find $\gamma_{\max} = 3.7 \times 10^7 [B_{-7}(kT / \text{keV})]^{1/2}$.

The estimates given above are valid as long as the electron Larmor radius is smaller than the coherence length of the magnetic field. Since the Larmor radius of the relativistic electrons is extremely small, $r_L \sim 0.1$ pc, this condition is satisfied even if the field coherence length is much shorter than the \sim Mpc scale of the intergalactic shocks.

All electrons with $\gamma_e > 200$ lose their energy over the age of the universe. The energy of these electrons is converted to a diffuse background of photons, which are produced through inverse-Compton scattering of microwave background photons. The initial energy of a microwave photon, $h\nu_0$, is boosted by the scattering up to an average value of $h\nu = (4/3)\gamma_e^2 h\nu_0$. Substituting the mean frequency of the microwave background photons for ν_0 , we find that the accelerated intergalactic electrons produce a diffuse background of radiation extending from the UV [$h\nu = 36(\gamma_e / 200)^2$ eV] and up to extreme γ -ray energies [$h\nu = 89\gamma_e^2$ GeV]. For a power-law distribution of relativistic electrons, $dn_e/dp_e = K p_e^{-2}$, the energy density of the scattered radiation

is predicted to be constant per logarithmic frequency intervals, $\nu(du/d\nu) = Kc/2 = u_e/2 \ln \gamma_{\max}$. Here $u_e = Kc \ln \gamma_{\max}$ is the energy density in relativistic electrons produced by the intergalactic shocks. If a fraction f_{sh} of the baryons in the universe were shocked to a (mass-weighted) mean temperature T , and a fraction ξ_e of the shock thermal energy was transferred to relativistic electrons, then $u_e = \frac{3}{2} \xi_e f_{\text{sh}} n_p kT = 5.1 \times 10^{-16} \xi_e f_{\text{sh}} (\Omega_b h_{70}^2 / 0.04) (kT/\text{keV}) \text{ erg cm}^{-3}$, where n_p is the average proton density, Ω_b is the cosmological baryon density parameter, and h_{70} is the Hubble constant in units of $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. By substituting $\ln \gamma_{\max} = \ln(4 \times 10^7)$, we then get

$$E^2 \frac{dJ}{dE} = 1.1 \left(\frac{\xi_e}{0.05} \right) \left(\frac{\Omega_b h_{70}^2}{0.04} \right) \left(\frac{f_{\text{sh}} kT}{\text{keV}} \right) \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \quad (1)$$

where $E = h\nu$, and J is the number flux of photons per solid angle. Adopting the result from hydrodynamic simulations of⁴ $f_{\text{sh}}(kT/\text{keV}) \sim 1$, the Big-Bang nucleosynthesis value of^{20,21} $\Omega_b h_{70}^2 = 0.04_{-0.027}^{+0.014}$ (based on the deuterium abundance), and the value of $\xi_e \sim 0.05$ inferred from non-relativistic collisionless shocks in the interstellar medium, we obtain a background flux of $\sim 1 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ in the photon energy range of 3 MeV to 100 GeV. As Figure 1 illustrates, this result is in excellent agreement with the γ -ray background detected by the EGRET instrument aboard the CGRO satellite¹.

The sky-averaged contribution of identified extragalactic sources, such as blazars (γ -ray loud active-galactic-nuclei), amounts to only $\lesssim 7\%$ of the extragalactic γ -ray flux³. As shown in Figure 1, the recent EGRET data is consistent with a luminosity function of faint, undetected blazars, which could account for only $\lesssim 25\%$ of the unresolved γ -ray background^{2,3}. The remainder of the hard γ -ray background is expected to be highly isotropic in our model because it is integrated over a large volume throughout the universe. Its large-angle fluctuations should be comparable (to within a factor of a few) to that of the hard X-ray background, of which²⁵ $\sim 40\%$ is contributed by early-type galaxies at $z \lesssim 1$, since these galaxies trace the same large scale structure as painted by the comic web of intergalactic shocks. This implies a root-mean-square fluctuation amplitude smaller than $\sim 5\%$ on angular scales larger than a degree²⁶. The predicted high level of isotropy can serve as a test of our model, as soon as the isotropy of the γ -ray background is measured to a higher precision than presently available. Another possible test is the spectral distortion induced in the microwave background band by the low-energy tail of the non-thermal intergalactic electrons. This distortion is, however, well below the upper limit inferred from the COBE satellite data²⁷.

At photon energies $\lesssim \text{MeV}$ the scattered background is sub-dominant relative to the cumulative flux produced by discrete sources, such as active galactic nuclei. In particular, the predicted scattered flux amounts only to $\sim 10\text{--}15\%$ of the soft X-ray background measured by ROSAT at 1–2 keV, and is consistent with the upper limit of $\sim 20\text{--}30\%$ on its unresolved fraction^{25,28}.

Most of the γ -ray background is produced during the latest episode of shock heating of the intergalactic gas at $z \lesssim 1$, since the mean gas temperature is expected to decrease rapidly with

increasing redshift⁴. Furthermore, the photons emitted at redshifts $z \gtrsim 0.5$ lose a significant fraction of their energy due to the expansion of the universe. A more accurate calculation of the γ -ray background can be achieved by simulating the hydrodynamic evolution of the intergalactic medium and injecting a population of accelerated electrons into each fluid element which passes through a shock, at all redshifts. Such a simulation can yield both the background flux and its statistical fluctuations on the sky. For a given cosmological model of structure formation, the derived background flux will be proportional to ξ_e , and will not depend on any other free parameters.

Although the warm ($\lesssim 10^7$ K) intergalactic medium is expected theoretically to include a major fraction of the baryons in the present-day universe, it has not been observed directly as of yet. The soft X-ray emission from intergalactic structures, such as sheets and filaments or galaxy groups, is often too faint to be detectable with current telescopes⁴. The observed cosmological density of stars²¹, $\Omega_\star h_{70} = 3.5 \times 10^{-3}$, is an order of magnitude smaller than the baryon density predicted by Big-Bang nucleosynthesis. If the γ -ray background indeed results from keV shocks in the intergalactic medium, then we can derive a lower limit on the mean baryon density required to produce its observed flux. This minimum is obtained by substituting $\xi_e = 1/2$ (equipartition) and $f_{\text{sh}} = 1$ in equation (1), yielding $\Omega_b h_{70}^2 \gtrsim 4 \times 10^{-3}$. The inferred lower limit is *larger* than the observed mass density in stars. Thus, if the reality of our model is proven, then this would not only explain the origin of the diffuse component of the γ -ray background, but also provide the first evidence for the “missing baryons” (note that even if the truly diffuse component amounts to only $\sim 20\%$ of the γ -ray background flux, the more plausible range of $\xi_e \lesssim 10\%$ yields a lower limit on the baryon density which is still larger than the mass density in stars).

In our model, the γ -ray background is produced in the dense filaments and sheets which channel gas from converging bulk flows in the intergalactic medium. The densest and hottest shocks occur at the intersections of these filaments around the locations of clusters of galaxies. Although the richest accreting clusters may be rare and contribute a small fraction of the background, they contain the brightest shocks in the sky and produce the strongest fluctuations in the diffuse γ -ray background. Direct detection of these shocks can be used to calibrate ξ_e in our model. Even a statistical detection of a cross-correlation signal between background fluctuations and other sources that trace the same large scale structure, such as galaxies, X-ray gas, the Sunyaev-Zel’dovich effect, or synchrotron emission from the high energy electrons in the intergalactic medium, can be used to prove the reality of our model. We predict that as cold gas goes through the strong virialization shock of an accreting cluster, it emits non-thermal radiation with photon energies between 30 eV and TeV. The shocked gas loses a fraction $\sim (4.5/7) \times \xi_e \sim 3\%$ of its thermal energy in this process. For $h\nu \gg 10$ keV, the cooling time of the corresponding relativistic electrons is shorter than a billion years. In this regime the total non-thermal luminosity of the cluster, L_{nt} , is limited by the time it takes the cluster gas to cross the virialization shock, i.e. $t_{\text{vir}} \sim (2 \text{ Mpc} / 2 \times 10^3 \text{ km s}^{-1}) = 10^9 \text{ yr}$. For a young cluster which shocks gas of total mass

M_{gas} to a virial temperature T_{gas} , the total (bolometric) non-thermal luminosity is

$$L_{\text{nt}} \sim \left(\frac{4.5\xi_e/7}{t_{\text{vir}}} \right) \left(\frac{M_{\text{gas}}}{m_p} \right) \left(\frac{3}{2} k T_{\text{gas}} \right) = 1.5 \times 10^{45} \left(\frac{\xi_e}{0.05} \right) \left(\frac{10^9 \text{ yr}}{t_{\text{vir}}} \right) \left(\frac{M_{\text{gas}}}{10^{14} M_{\odot}} \right) \left(\frac{k T_{\text{gas}}}{5 \text{ keV}} \right) \text{ erg s}^{-1}. \quad (2)$$

(The total cluster mass, including the dark matter, is typically an order of magnitude larger than M_{gas} .) The luminosity per each logarithmic interval in photon energy, anywhere between 30 eV and TeV, is $\sim 0.1 L_{\text{nt}}$. This emission component would affect estimates of the gas temperature and the thermal luminosity of young clusters which form through shocking of cold gas. However, the high-energy emission would be suppressed in the weak shocks that result from mergers of pre-existing clusters which contain pre-heated gas, since the energy distribution of the accelerated electrons is steeper for weak shocks⁸. As a cluster relaxes to hydrostatic equilibrium and ages, its non-thermal luminosity declines. The emission of hard radiation disappears almost entirely as soon as there is no strong shocking of gas. At a perfectly quiescent state of hydrostatic equilibrium, the non-thermal radiation spectrum cuts-off above a photon energy, $h\nu \sim 0.5 \text{ keV} (\tau/3 \times 10^9 \text{ yr})^{-2}$, for which the electron cooling time equals the cluster age, τ . Detection of this cut-off can be used as a method of dating the time that has passed since the last major accretion episode of cold gas by the cluster. Most relaxed clusters with ages $\tau \gg 10^9 \text{ yr}$, are expected to show only weak non-thermal emission at $h\nu \gtrsim 10 \text{ keV}$. We note that the detection of nonthermal X-ray emission has been reported recently for several clusters^{16,17,29}. In addition, some X-ray clusters possess radio halos³⁰ which may result from synchrotron emission by the residual population of relativistic electrons in the cluster magnetic field.

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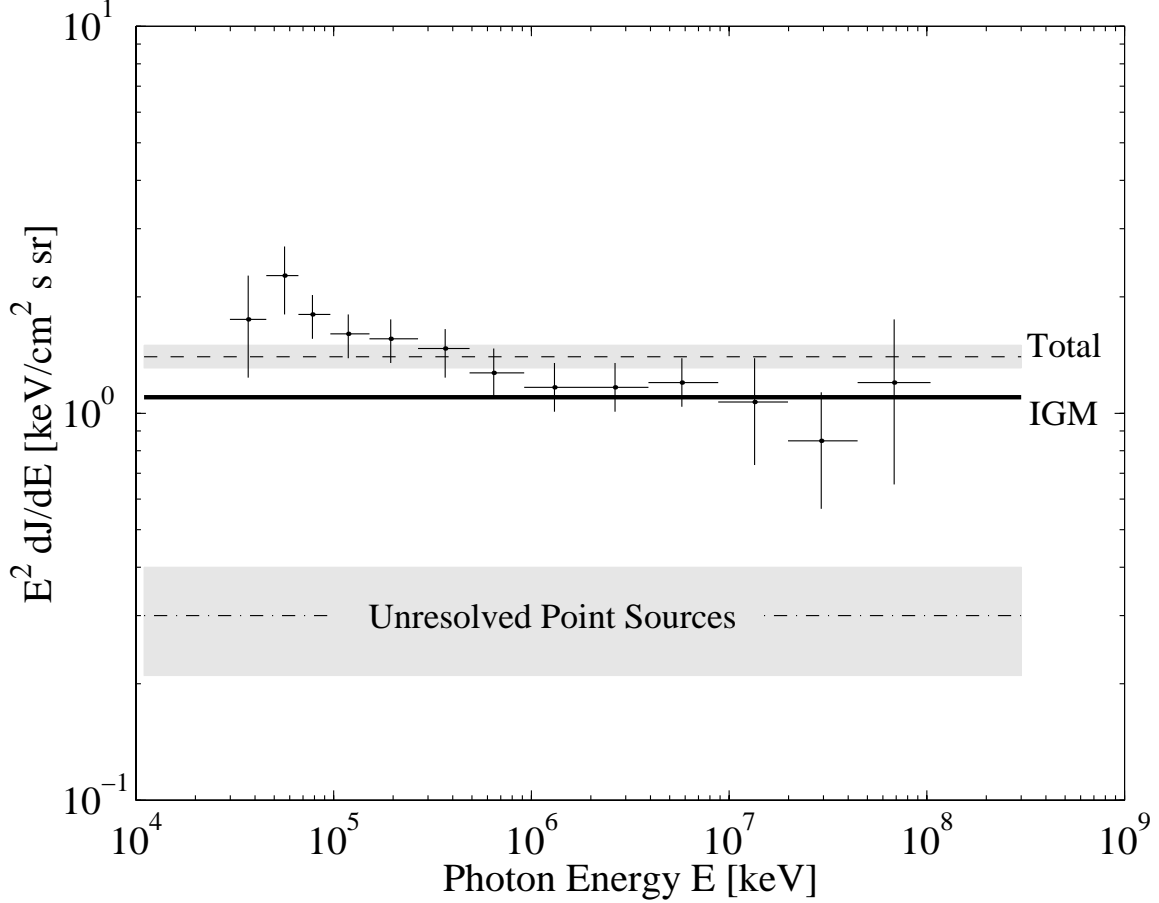


Fig. 1.— Spectrum of the unresolved γ -ray background. Points with error bars are the observed data from EGRET¹. The lower shaded region shows the expected contribution from unresolved point sources, based on empirical modeling of the luminosity function of blazars^{2,3}. The solid line shows the diffuse emission from intergalactic shocks, according to Eq. (1) with $\xi_e = 0.05$ and $f_{\text{sh}} kT = 1$ keV. The upper shaded region shows the sum of these contributions, which provides an excellent fit to the data. The blazar contribution was calibrated^{2,3} only by the total flux in photons with energies $E > 10^5$ keV; hence, the small deviations of some data points from the upper shaded region might be due to uncertainties in the cumulative blazar spectrum. Although the background flux predicted by Eq. (1) is independent of the magnetic field strength in the intergalactic shocks, the maximum energy of scattered photons does depend on the field strength and is given by, $h\nu_{\text{max}} \sim 1.2 B_{-7}(kT/\text{keV})$ TeV. Photons with energies $\gtrsim 1$ TeV produce an electron-positron pair as they scatter on the infrared background^{22,23}. The pair cools again by scattering microwave photons, which may in turn produce new pairs. The energy originally stored in photons with $h\nu \gtrsim \text{TeV}$ is spread smoothly over the 100 MeV to TeV energy range²⁴, and might raise the existing flux there. However, since in our model only a small fraction of the electrons are accelerated to the energy required for the production of $h\nu \gtrsim \text{TeV}$ photons, we expect this effect to be small.

